NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 897

KNOCKING COMBUSTION OBSERVED IN A SPARK-IGNITION ENGINE WITH SIMULTANEOUS DIRECT AND SCHLIEREN HIGH-SPEED MOTION PICTURES AND PRESSURE RECORDS

By GORDON E. OSTERSTROM

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight$=mg$

g Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass$=\frac{W}{g}$

I Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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Figure 9(b): The numerals designating the number of frames B.T.C. should be increased by one; that is, frame 32 should be frame 33, frame 34 should be frame 35, and so forth.

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SUMMARY

Simultaneous direct and schlieren photographs at 40,000 frames per second and correlated pressure records were taken of knocking combustion in a special spark-ignition engine to ascertain the intensity of certain end-zone reactions previously noted from schlieren photography alone.

The first stages of the autoignition process as seen in the schlieren photographs emitted insufficient light to be photographed directly. In one instance, the last stages of the preknock autoignition process emitted enough light to be photographed. A violent propagated homogeneous autoignition, or a similar phenomenon, previously observed, was again observed. The pressure records show autoignition of varying violence before the passage of a probable detonation wave. Extensive autoignition without occurrence of gas vibrations was seen in one explosion.

INTRODUCTION

All previous photographic investigations of combustion and knock employing the NACA high-speed motion-picture camera have been conducted with schlieren photography instead of photography of the combustion by its own light, or "direct" photography (reference 1). These investigations demonstrated two separate and different phenomena in addition to ordinary combustion, namely, a relatively slow preknock reaction termed "autoignition" and a fast reaction termed the "explosive knock reaction." In schlieren photography, irregularities in the refractive index of the gaseous contents of the combustion chamber are photographed. A flame or other reaction occurring within the combustion chamber causes localized differences in index of refraction that can be recorded. With the type of schlieren system used for these studies, the actual temperatures cannot be found. Inasmuch as knock is a thermochemical phenomenon, knowledge of end-gas-reaction temperatures is of prime importance in the study of knock. The schlieren method was used, however, because the flame reaction could thereby be easily photographed with an exposure of 0.000025 second. Direct photographs, by showing that reactions have proceeded to the luminous state, do offer a rough conventional method of distinguishing between low- and high-temperature reactions. Direct flame photographs, however, have certain disadvantages. They afford no means of determining the absence of a flame because of the possibility of insufficient detection sensitivity. Moreover, such photographs are indistinct in outline and very difficult to obtain with an exposure of 0.000025 second without the use of additives to increase actinic radiation. In order to obtain any photographs at all, extremely fast camera lenses and films must be used, which yield images whose definition is inferior to that obtained with the schlieren photographs.

The investigation reported, which was conducted during 1946–47 at the NACA Cleveland laboratory, is based on experiments that simultaneously utilize the respective advantages of both schlieren and direct photography. Motion pictures simultaneously taken with both schlieren and direct photography have been chronologically correlated with one another and with a pressure record in an attempt to determine whether preknock end-gas reactions, as seen in schlieren photographs, may represent flame. This report is based on photographs of only nine explosions; therefore, it cannot be regarded as having universal applicability. Individual explosions, however, are assuredly correctly described because the single motion picture is composed of hundreds of photographs. Each photograph may be thought of as a kind of data point with adjacent photographs as check points. Thus a given phenomenon shown by a single motion-picture series unquestionably happened at least once. Questions of the possibility, but not necessarily the probability, of the reoccurrence of a given phenomenon can thus be answered.

APPARATUS AND PROCEDURE

Engine cylinder and piston.—The engine used was specifically designed for photographing the entire volume of burning gas within it during a single explosion; it is a single-cylinder spark-ignition engine with a 4⅛-inch bore and 7-inch stroke. A simplified sectional view of the engine is shown in figure 1. The glass window forming the upper wall of the combustion chamber is made of two disks of 1-inch-thick plate glass. A concave spherical-surface mirror made of stellite is fastened to the top of the piston by three screws, which appear in the schlieren photographs as three black spots near the edge of the mirror. The combustion chamber is 4⅛ inches in diameter. Openings around its walls provide access for a spark plug, a piezoelectric pickup for pressure measurements, and a fuel-injection nozzle. After each explosion the stellite mirror, the cylinder walls, and the windows are polished with optical rouge suspended in a mixture of water and a wetting agent.

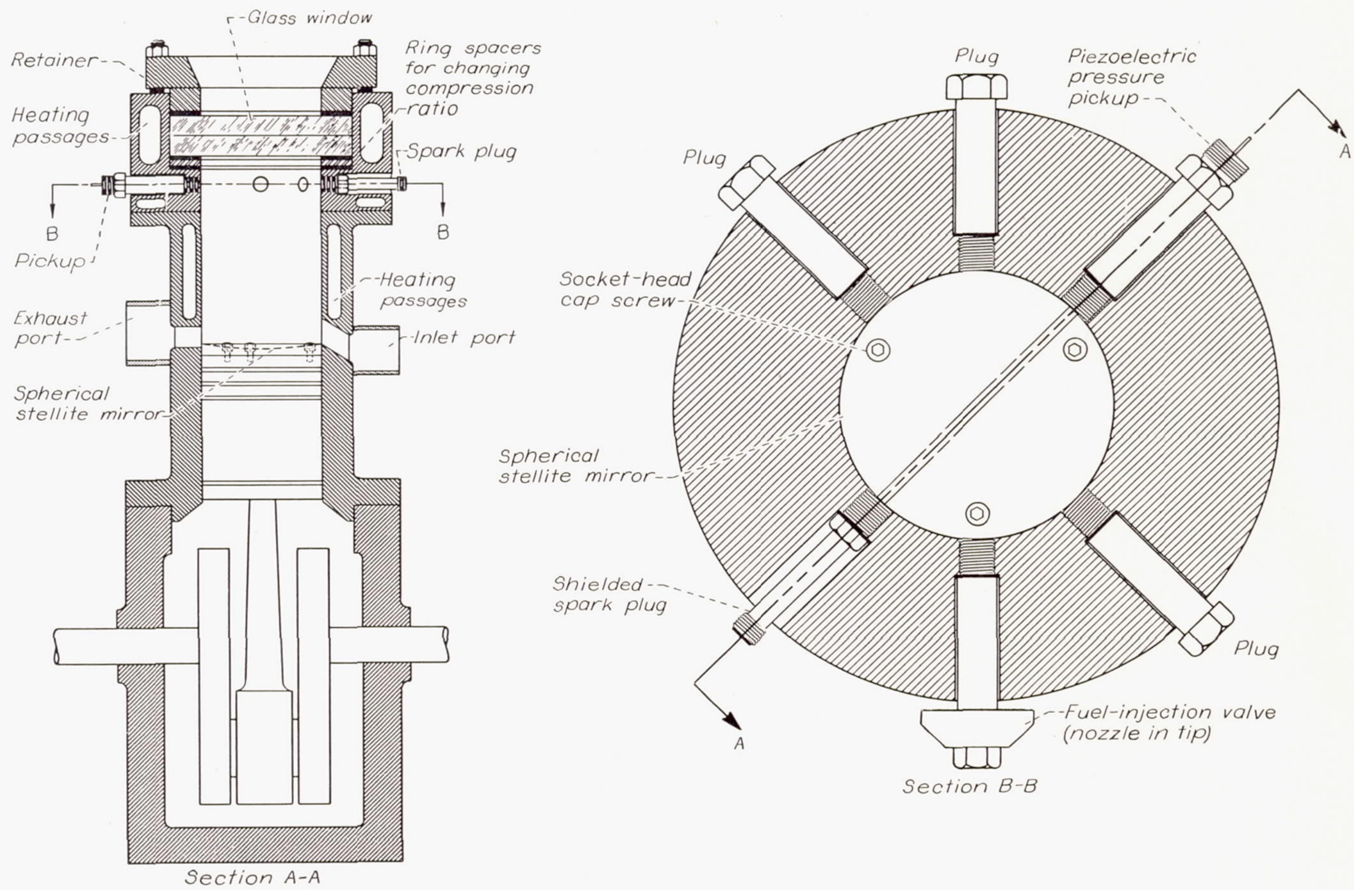


FIGURE 1.—Simplified longitudinal and cross sections of engine.

The piston is operated without oil because oil would cloud the windows and the mirror and make irregularities in the pictures. In addition, burning oil droplets would add to the difficulty of interpreting the photographs. The only lubricant is a small amount of graphite occasionally rubbed onto the cylinder walls.

Air system.—The air flow in and out of the cylinder is controlled by the piston as it covers and uncovers inlet and exhaust ports near the bottom of the piston stroke. A diagram of the air system that was used to measure and control engine air-flow, pressure, and temperature conditions is presented in figure 2. The air flow through the engine is adjusted by altering the difference in pressure between the inlet and outlet passages. This pressure difference, as well as the absolute pressure in the cylinder before compression, may be adjusted by manipulating automatic inlet and precompression outlet valves. An orifice flowmeter and a thermocouple are installed in the inlet-air lines; mercury manometers measure the pressure in the inlet- and outlet-air lines. The air is electrically heated.

Fuel system.—The fuel is admitted to the combustion chamber in the liquid state. A triple-orifice nozzle discharges the fuel at high velocity from the injection valve into the combustion chamber. The desired quantity of fuel is forced through the injection valve and out the orifices at the proper moment by the automatic release of a single-stroke spring-driven piston pump. The pump meters the fuel to an accuracy of ± 2 percent. This type of system fails to insure a homogeneous mixture of fuel and air. Mixing the fuel and the air continuously before admission to the engine was impractical because the compression of the mixture was sufficient to explode the charge every revolution. This situation would be intolerable, as the window would become coated with soot and might even crack from temperature stresses. The fuel system was carefully purged of gases before use and was kept under pressure to prevent vapor bubbles from forming in the hot injection valve and connecting tubing. The circulating-type system previously used in NACA investigations was not used because the proper type of circulating pump was unavailable when the apparatus was constructed.

Pressure-recording system.—The arrangement of the explosion-pressure-recording system is shown in figure 3. A quartz piezoelectric pressure pickup of the flat-spring-

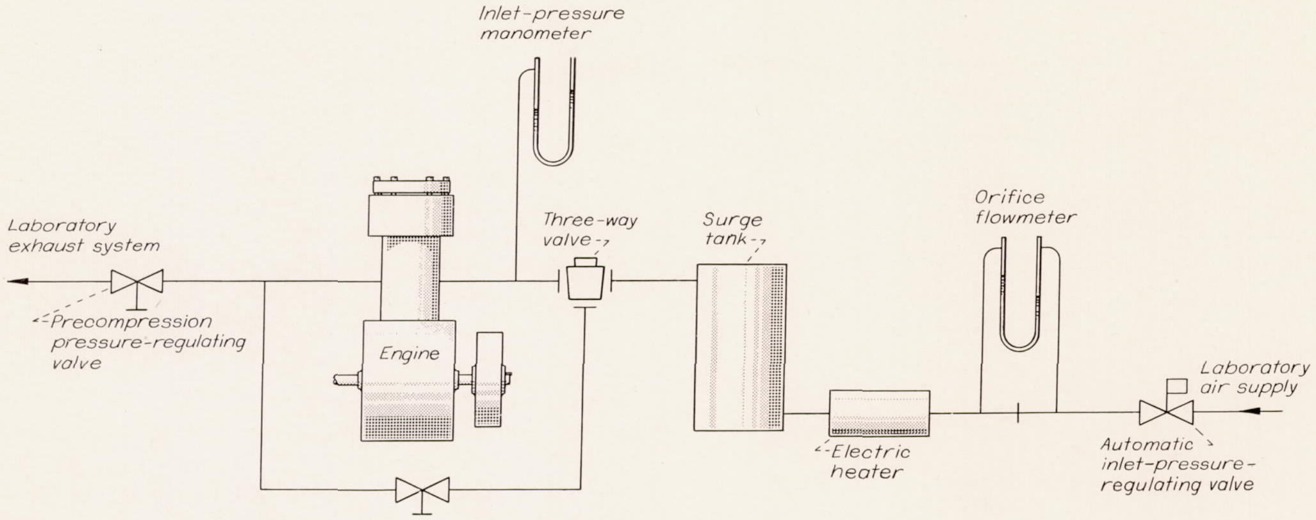


FIGURE 2.—Diagrammatic sketch of air system.

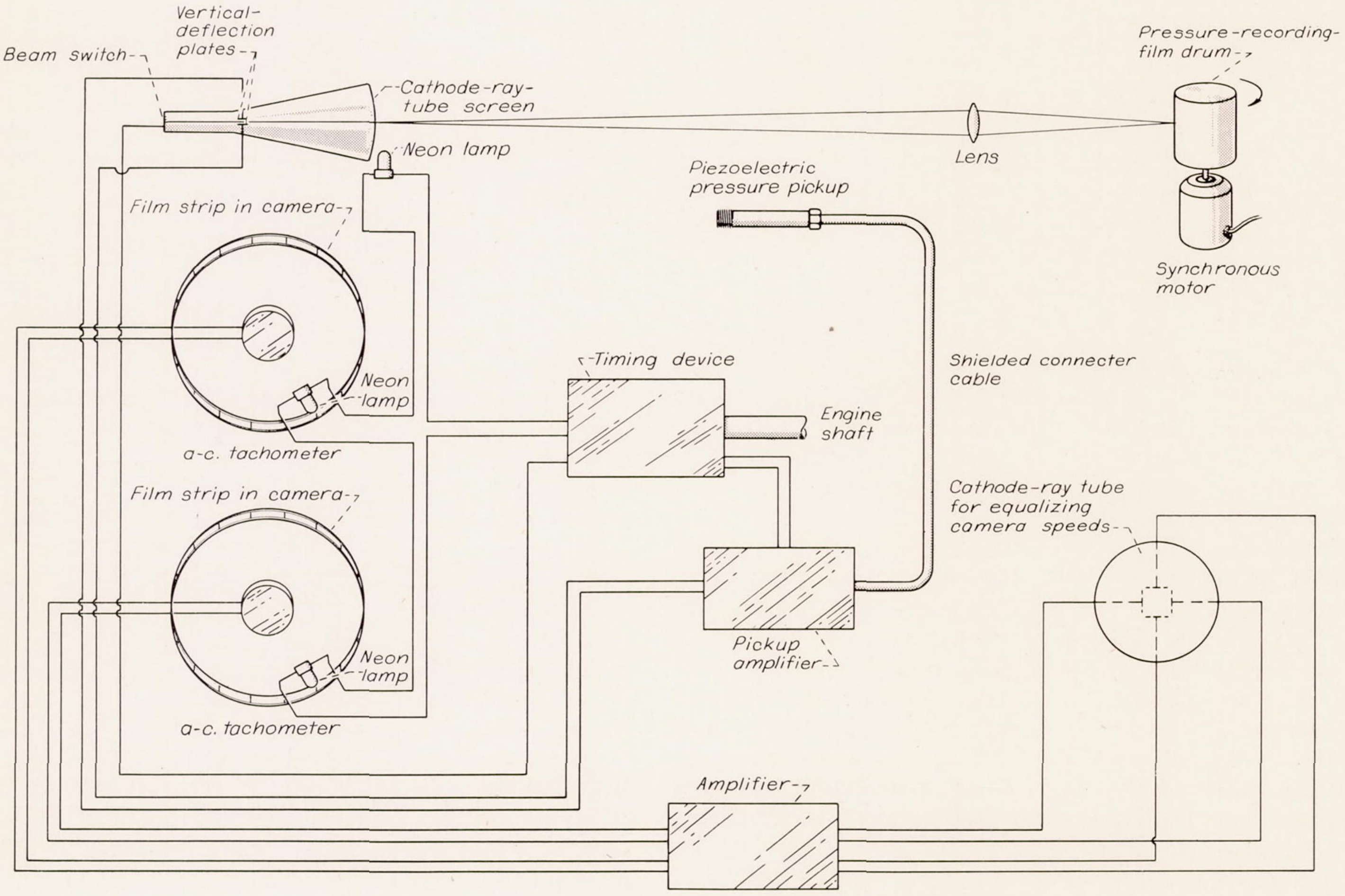


FIGURE 3.—Diagrammatic sketch of timing and pressure-recording apparatus.

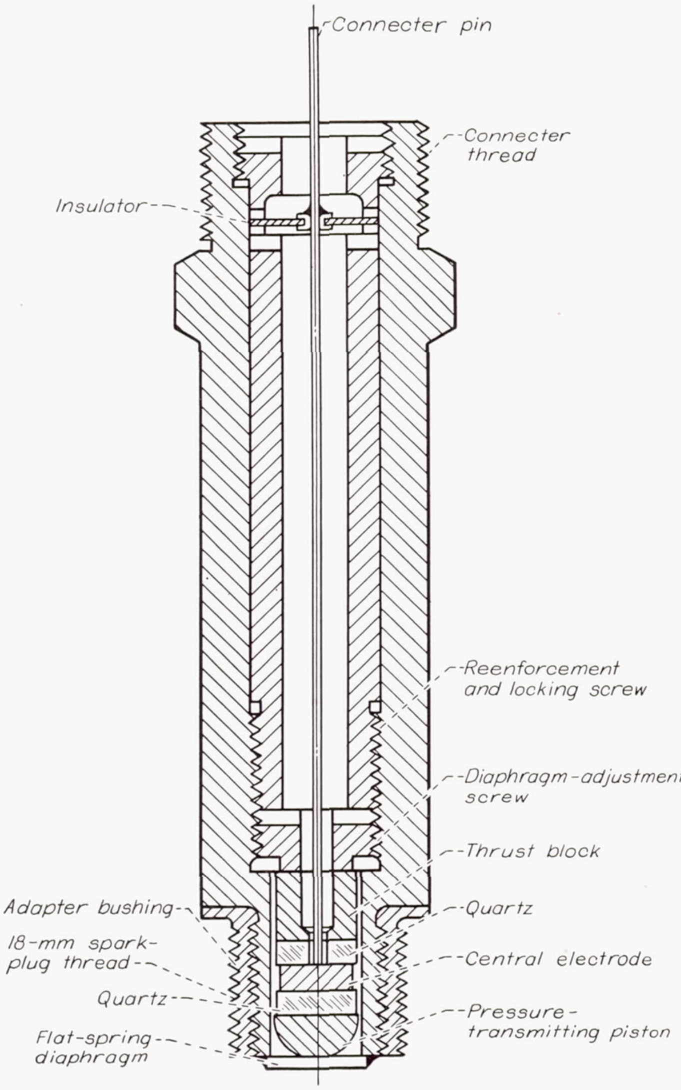


FIGURE 4.—Piezoelectric pressure pickup.

diaphragm type (fig. 4) was used to measure combustion-chamber pressures. The dynamic performance of this instrument was measured by a method (reference 2) in which the pickup diaphragm is driven by the inverse piezoelectric effect. The motions of the diaphragm were measured by using it as one plate of an electric condenser, the voltage variations of which can be observed as the frequency of the sinusoidal constant-amplitude driving voltage is varied while the charge in the condenser remains constant. Tests performed by this method show that the instrument has no objectionable natural frequencies through the test range and will probably not be set into vibration by ordinary combustion shocks. It should be noted, however, that the response of the pickup is far from uniform as the frequency is varied from 700 to 40,000 cycles per second. For example, the unit is six times as sensitive to 16,500-cycle-per-second vibrations as it is to 700-cycle-per-second vibrations.

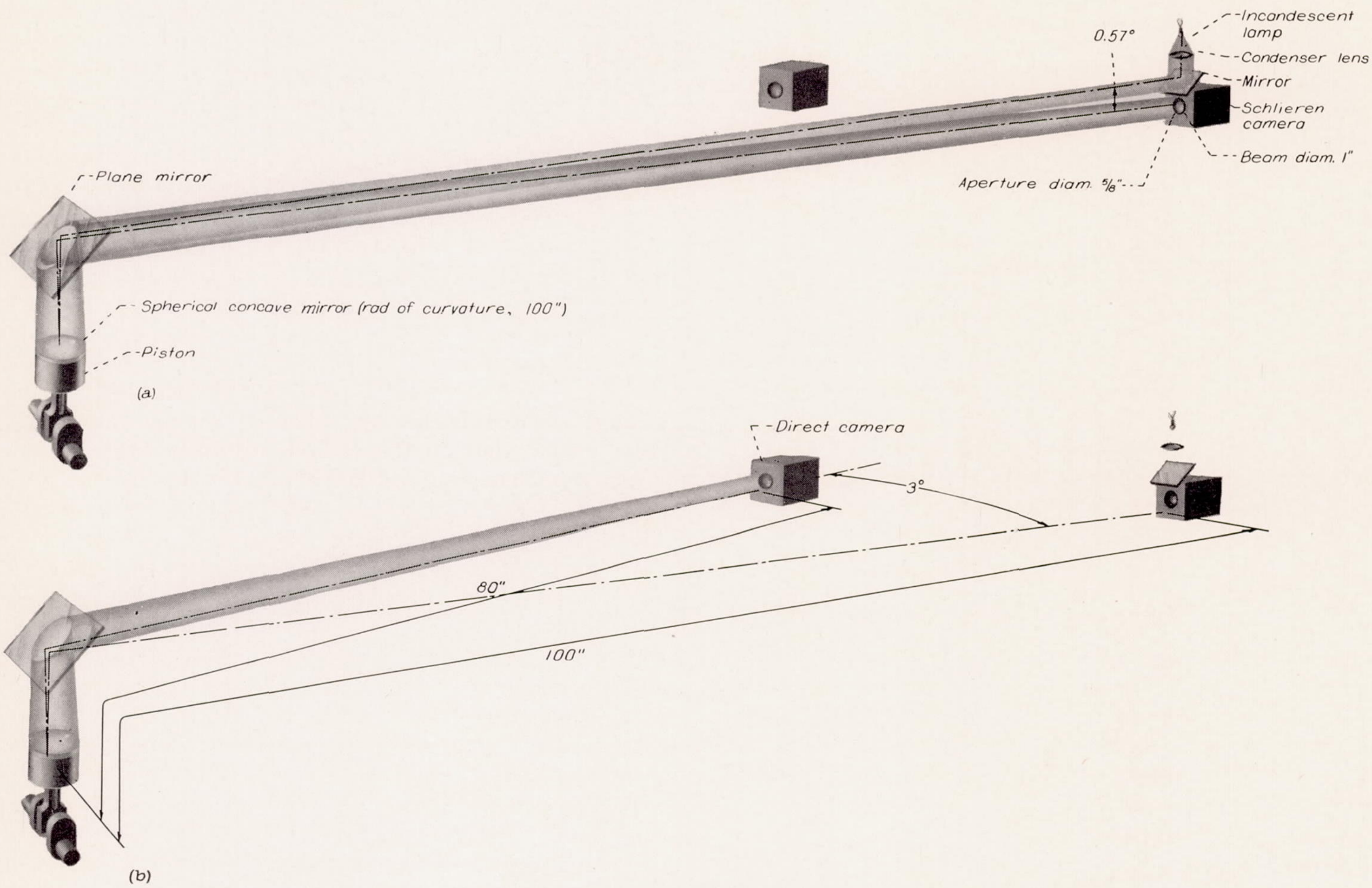
In operation, the output of the pickup passes through a low-frequency compensating network and thence to an amplifier developed especially for this type of application (reference 3). The output of the amplifier passes to the vertical-deflection plates of a cathode-ray tube. An image of the tracing spot on the screen of the cathode-ray tube is formed by a lens on a film strip wrapped once around a cylinder rotated by a synchronous motor. The cathode-ray-tube circuits are fitted with a switch connected to the crankshaft that turns the electron beam on at the proper moment and keeps it on for about one revolution of the film cylinder. The amplifier remains ineffective for a brief period after the electron beam is turned on. This lag causes a straight line to appear on the pressure record that represents the average motoring pressure of the combustion chamber as the engine rotates before the single explosion.

The average voltage input to the cathode-ray tube during the motoring period is zero because leakage to and from the electrode plates in the pickup maintains the average charge at zero. The voltage output corresponding to the average motoring pressure therefore is zero. The neutral position of the tracing spot on the cathode-ray-tube screen is at rest with zero deflecting voltage applied. Hence, even though the pickup and the oscilloscope are unconnected, the neutral position of the spot on the screen corresponds to the average motoring pressure in the cylinder. When the amplifier begins to function, the tracing spot follows the instantaneous pressure.

In order to use the pressure records quantitatively, some datum pressure (such as the average motoring pressure), the pressure-deflection constant of the tracing spot on the recording film, and the linear speed of the recording film must be known. The average motoring pressure was obtained by measuring the pressure in a vessel that was temporarily connected to the combustion chamber by a restricted passage. The deflection constant was determined by analyzing pressure records of the engine with a range of values of average and peak compression pressures. The peak compression pressure was measured with a CFR peak-compression-pressure gage. The relation between the deflection constant and the time abscissa was such that the pressure-time record was much flatter than records shown in previous NACA reports. In order to compare the present pressure records with previous NACA records, the slopes of the present records should be increased by a factor of about 10. Slight irregularities on pressure records of the present series might have appeared as discontinuities on previous pressure records. The linear speed of the recording film is fixed by the synchronous electric motor, which is driven from the city electric-power system.

Time-correlation system.—The time-correlation device is also shown in figure 3. Each high-speed camera contains one neon lamp. Another lamp is placed in the pressure-recording system at the edge of the cathode-ray-tube screen and in line with the motion of the spot on the screen. When these lamps flash, they mark the camera and pressure-record films. All three lamps are in series with one another and with a device that gives two distinct pulses of current through them. The first pulse occurs when the engine piston is approximately at top center. The subsequent pulse comes at about 20° A.T.C. The simultaneous markings on the two high-speed camera films and on the pressure record permit a time correlation of three records.

In order that the direct and schlieren high-speed motion pictures be directly comparable when laid side by side, the camera rotors had to operate at the same speed at the moment the explosion occurred. Just before the engine was



(a) Operation of schlieren camera.
(b) Operation of direct camera.
FIGURE 5.—Diagrammatic sketch of optical systems of high-speed cameras. (Shaded parts represent light path.)

fired, the difference between the speeds of the two rotors was reduced to a satisfactory minimum through the use of a cathode-ray tube as a frequency comparator for the alternating voltages of the two electric camera tachometers. Comparison of the distances between timing marks on the two high-speed-camera film strips showed that the speed equalization was sufficiently accurate to permit direct comparison to within 1/15 frame near the time of knock.

Cameras.—The NACA high-speed motion-picture camera, two of which were used, is described in detail in reference 4. The positions of the cameras with respect to the combustion chamber are indicated in figure 5.

One camera is arranged to take bright-field schlieren photographs. With this type of schlieren system, irregularities in index of refraction (such as those caused by thermal gradients) are indicated by black areas on a normally white background. The light-gathering capacity of the schlieren camera is ordinarily inadequate to record combustion-chamber luminosity. The method of operation of the schlieren system is shown in figure 5. A beam of light from the incandescent lamp is directed at the mirror on the piston top. The mirror reflects most of the light that falls on it, forming a convergent beam. A large part of the beam reflected from the piston top is converged through the objective lens of the camera. Should there be an irregularity at a point in the combustion chamber that deflects a part of the beam in such a manner that the light passing through the irregularity is not converged into the camera, the irregularity will appear black on the photographic positive. The irregularity is unilluminated as far as the camera is concerned. The camera objective lens is focused on the mirror and the adjacent combustion chamber. The physical dimensions of the schlieren systems are shown in figure 5. These dimensions fix the sensitivity of the system.

The direct high-speed camera is equipped with a lens of aperture sufficient to record combustion-chamber radiations with a photograph-taking rate equal to that of the schlieren camera when panchromatic film hypersensitized by the mercury-vapor process (reference 5) is used.

The two high-speed cameras view the combustion chamber along different lines. The schlieren camera views the chamber along a line that is within 1° of perpendicularity to the mirror on the piston top. The direct camera views the chamber along a line that makes an angle of about 3° with the line of view of the schlieren camera. The oblique viewing angle of the direct camera causes the combustion-chamber images formed by it to be slightly elliptical, turned, and cut off around part of the edge when compared with the schlieren photographs. These differences in shape, orientation, and size of the photographs are small enough to be unimportant for the scope of the present work.

Engine conditions.—The engine conditions used were:

Inlet-air temperature, °F	350
Compression ratio	7.8

Engine temperature, °F	212
Fuel-air ratio	0.19
Preinjection fuel temperature, °F	212
Inlet-air pressure	approximately atmospheric
Ignition spark, deg B.T.C.	20
Engine speed, rpm	600
Fuels	n-heptane and M–4 reference fuel

PRESENTATION OF RESULTS

Enlarged positive prints have been prepared from the original motion-picture negatives and are presented in figures 6 to 14. The entire motion-picture negative strip from a single explosion includes several hundred frames. In order to permit large reproductions, only those frames showing the most pertinent phenomena are included. The progress of the normal flame is omitted.

The schlieren field is uniformly white before the passage of the flame. Inspection of motion pictures of runs that failed to ignite for various reasons shows that the schlieren field retains the same appearance throughout the time when the combustion reactions should have occurred.

A dashed white line between adjacent frames indicates that intermediate frames have been omitted. If none are omitted, the period between complete exposure of successive frames is 0.000025 second. The frames are numbered according to their order before or after piston top center; top center is indicated as zero. The frames after top center have negative signs before the frame number. The direct and schlieren photographs are presented in parallel rows correlated to less than one frame with respect to time.

Circles have been drawn in to represent the outline of the combustion chamber. The position of spark plug, pressure pickup, and fuel-spray nozzle may be seen in the combustion-chamber cross section in figure 1. In general, the combustion front proceeds from the spark at the lower left toward the pressure pickup at the upper right.

In the schlieren photographs, the normal flame is indicated by an irregular dark band on a white field. The front of the band is frequently distinct but the rear is usually indefinite. Mottling ahead of the flame front indicates some form of end-zone reaction. The darker the mottling, the more intense is the reaction. In the direct pictures, light areas represent recordable luminosity (except for occasional photographic defects).

The entire pressure record is presented together with an enlargement of the portion involving knock. On the enlargement, points on the curve corresponding to motion-picture frames are noted. Those characteristics of the explosions obtained from the pictures and pressure records that can be presented in tabular form are given in table I.

The schlieren photographs of knocking combustion are similar in most respects to those described in previous NACA reports (references 1, 6, and 7). Certain points of difference, however, will be emphasized. The several phases of knocking combustion will be described in detail in the following discussion.

RESULTS AND DISCUSSION

NORMAL FLAMES

The luminosity of the normal flame preceding knock varies greatly from explosion to explosion. Only a few bright points in the burned region are shown in figures 6 and 7. No general luminosity is recorded until shortly before the accelerated end-zone reactions. Figure 8 shows a brilliant flame with slight gradations in luminosity up to the leading edge of the flame. Figure 9 shows a brilliant illumination near the spark plug with gradual fading toward the leading edge of the flame. The faintly luminous area in this run shows points similar to those in figures 6 and 7 but less bright. Figure 10 shows a faint and somewhat flocculent flame. No two flames have the same general appearance back of the flame front. The contours of the flames, as seen in direct and schlieren pictures taken simultaneously, obviously do not closely correspond in most cases.

The large variation in the intensity of the actinic luminosity from one explosion to the next is incompletely understood. The amount of fuel sprayed into the cylinder was 185 percent greater than the stoichiometric requirement. This quantity was the minimum that would consistently explode. How much of this fuel actually evaporated in the charge air is unknown. Some of it may have been projected across the combustion chamber and clung as a liquid to the opposite wall. If the amount thus rendered unavailable for mixing with the air varied with successive explosions, some of the variation might be explained.

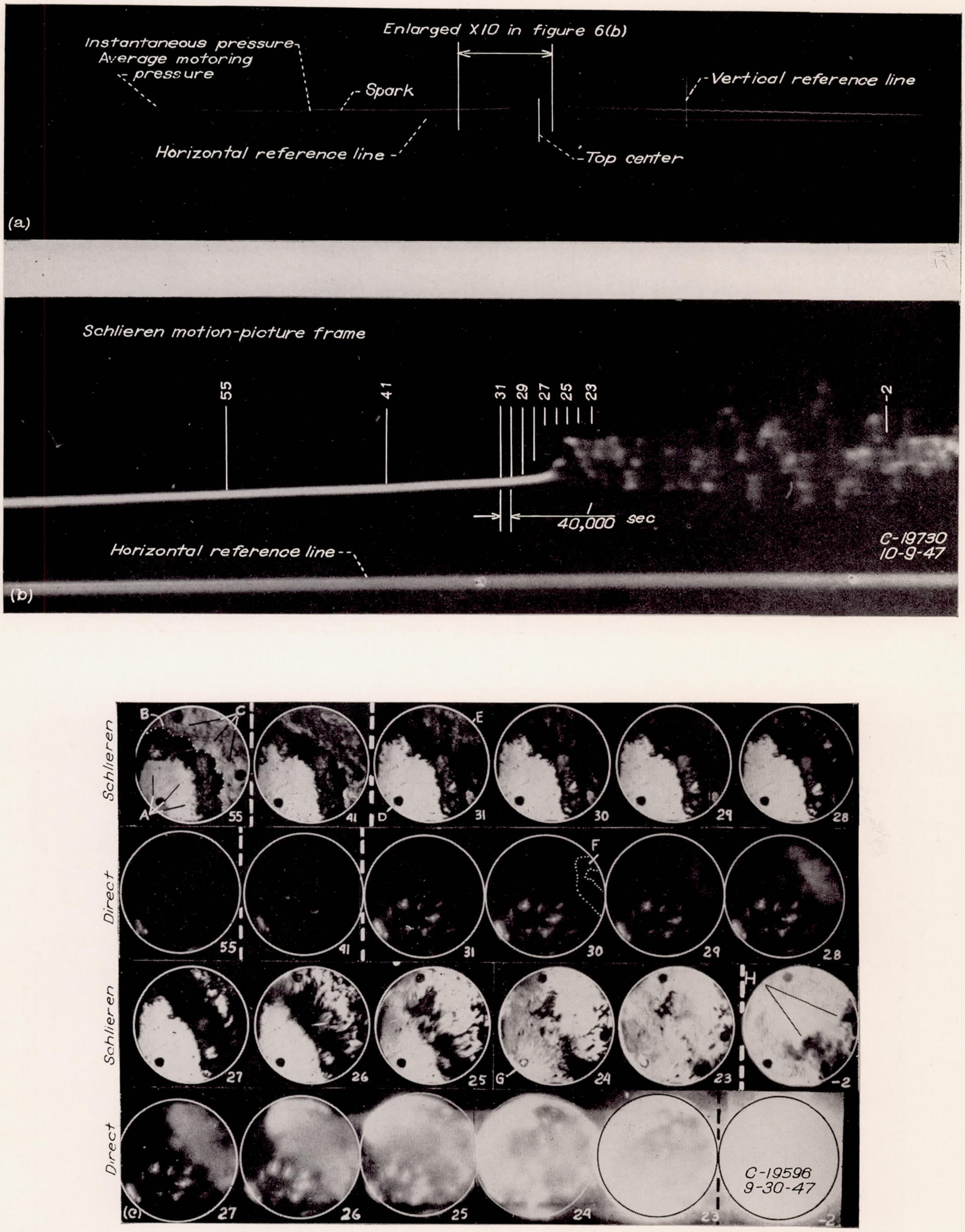
PREKNOCK END-ZONE REACTIONS

All the schlieren photographs indicate, by darkening or extensive mottling, slow reactions in the end zone preceding, by many frames, development of recordable end-zone luminosity and the violent pressure changes denoting knock.

TABLE I.—SUMMARY OF QUANTITATIVE DATA

	1	2	3	4	5	6	7	8
Figure	Fuel	Number of frames by which gradual end-zone schlieren darkening (or mottling) precedes luminescence in end zone	Number of frames from end-zone luminosity to first pressure pulse	Time when knock occurs (° B.T.C.)	Pressure at moment when first pulse occurred (lb/sq in. abs.)	Number of frames by which sudden blackening of schlieren pattern precedes first pressure pulse	Computed end-gas temperature at moment when knock occurred (°F)	Pressure ratio undergone by end gas in being raised to preknock conditions
6	n-heptane	30	3½	2.0	510	5	1390	35
7	M–4	53	−1	−1.0	560	0	1430	39
8	n-heptane	40	−1	2.0	480	0	1360	33
9	do	58	2	4.0	420	4	1310	29
10	do	70	----	----	[a] 450	----	[a] 1340	[a] 31
11	do	113	2	0	480	0	1360	33
12	do	25	−3	−2.0	510	−1	1390	35
14	M–4	27	−2½	1.0	510	0	1385	35

[a] Conditions of end gas when abnormal pressure rise presumably began.



(a) Entire pressure record.
(b) Enlarged portion of pressure record; magnification, X10.
(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, white dots (insertion) outlining first end-zone luminosity; G, gases within screwhead socket rendered luminous by pressure wave; H, smoke.

FIGURE 6.– Knocking combustion of n-heptane fuel showing feeble normal flame luminosity and brilliant end-zone luminosity.

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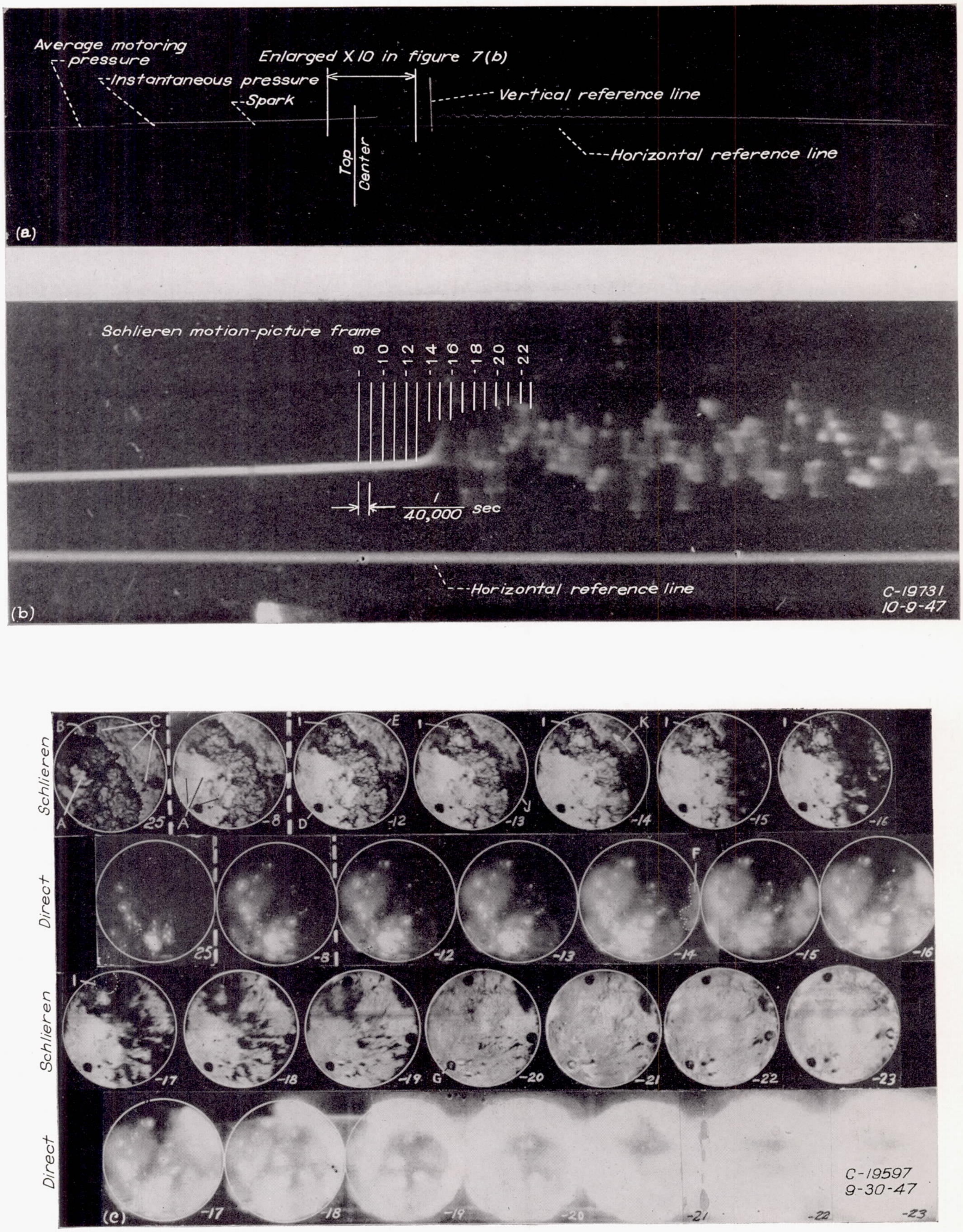

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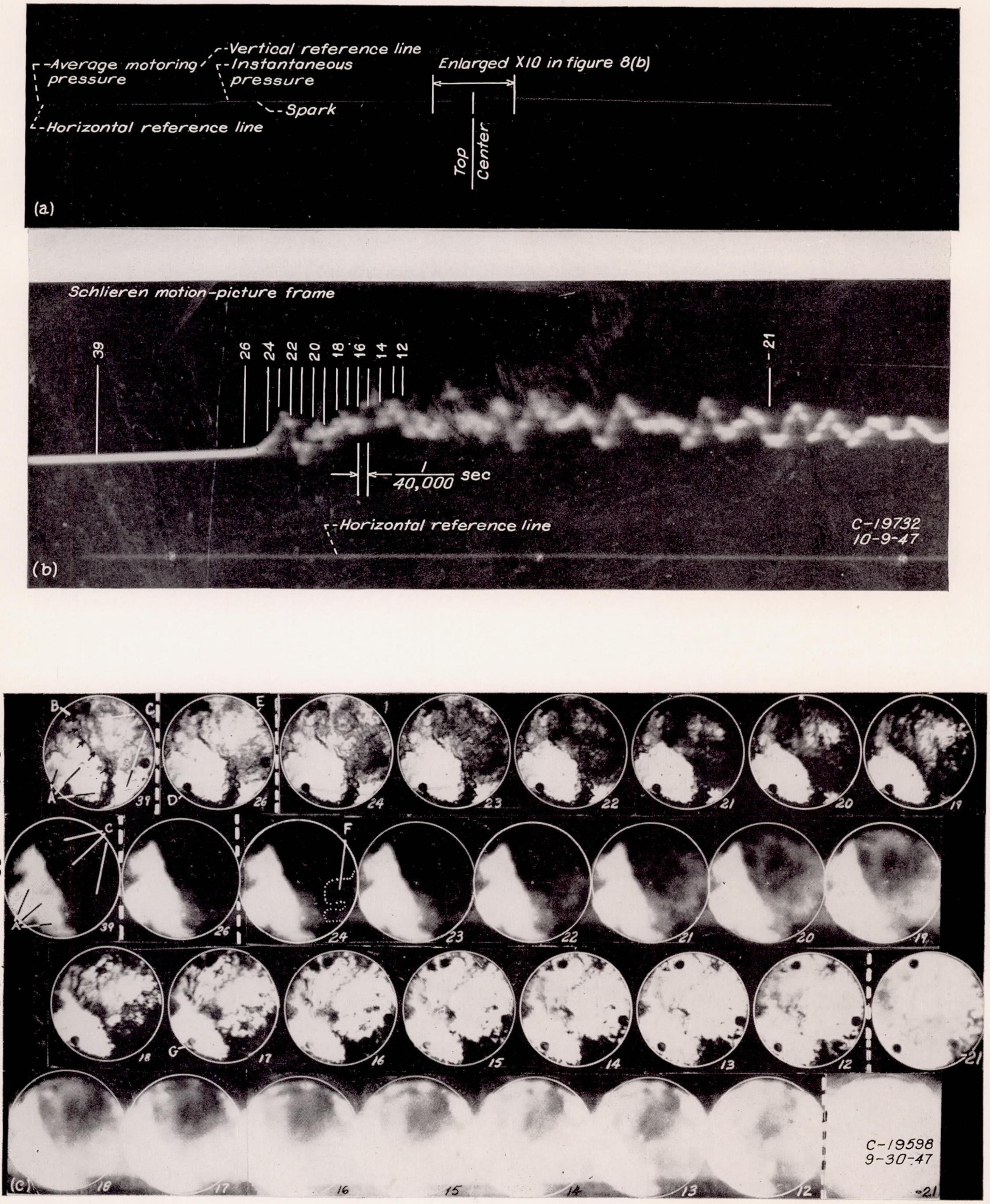
FIGURE 7.—Knocking combustion of M-4 fuel showing propagated homogeneous autoignition.

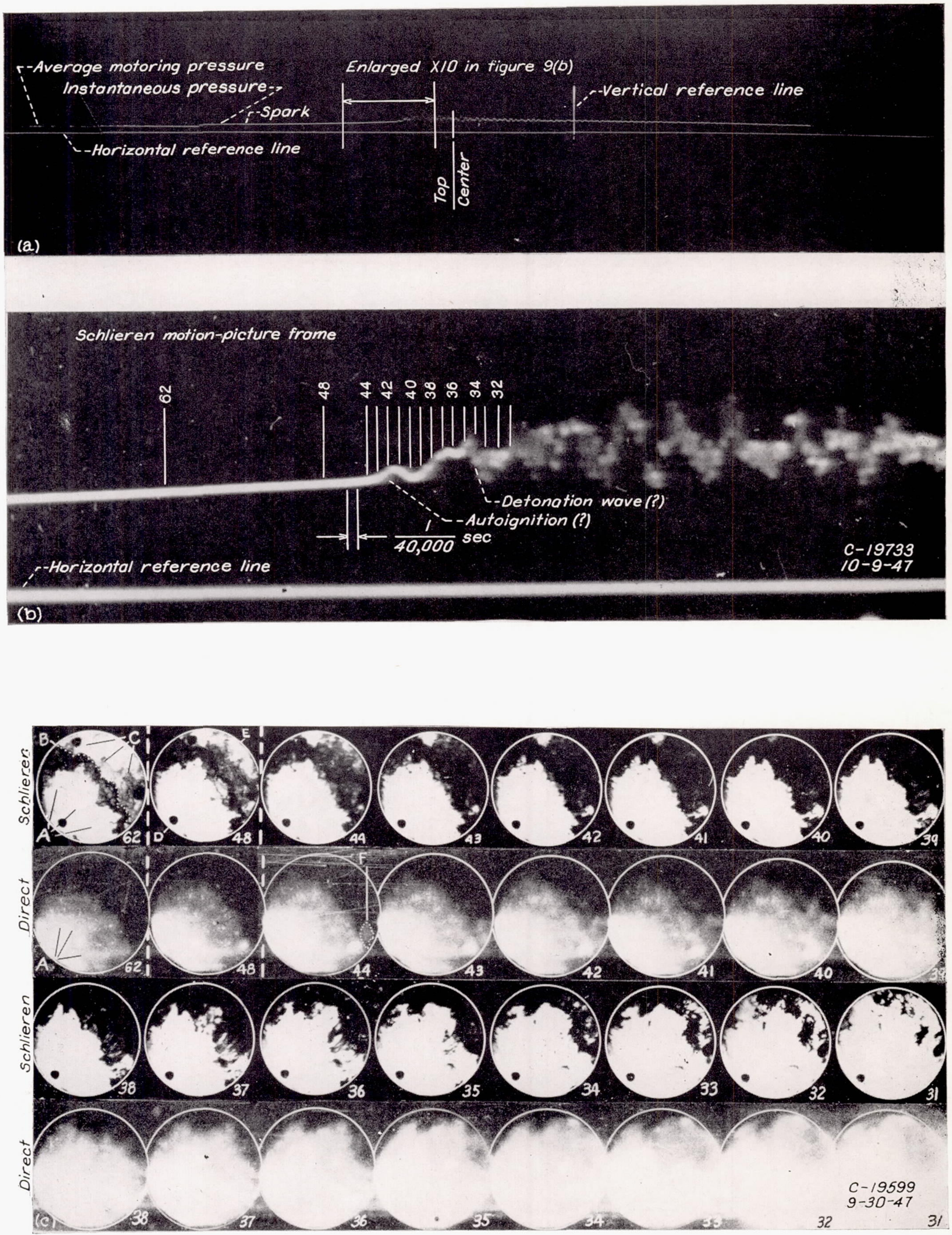


(a) Entire pressure record.

(b) Enlarged portion of pressure record; magnification, X10.

(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, white dots (insertion) outlining first end-zone luminosity; G, gases over screwhead socket rendered luminous by pressure wave.

FIGURE 8.—Knocking combustion of n-heptane fuel showing uniform, diffuse development of end-zone luminosity.

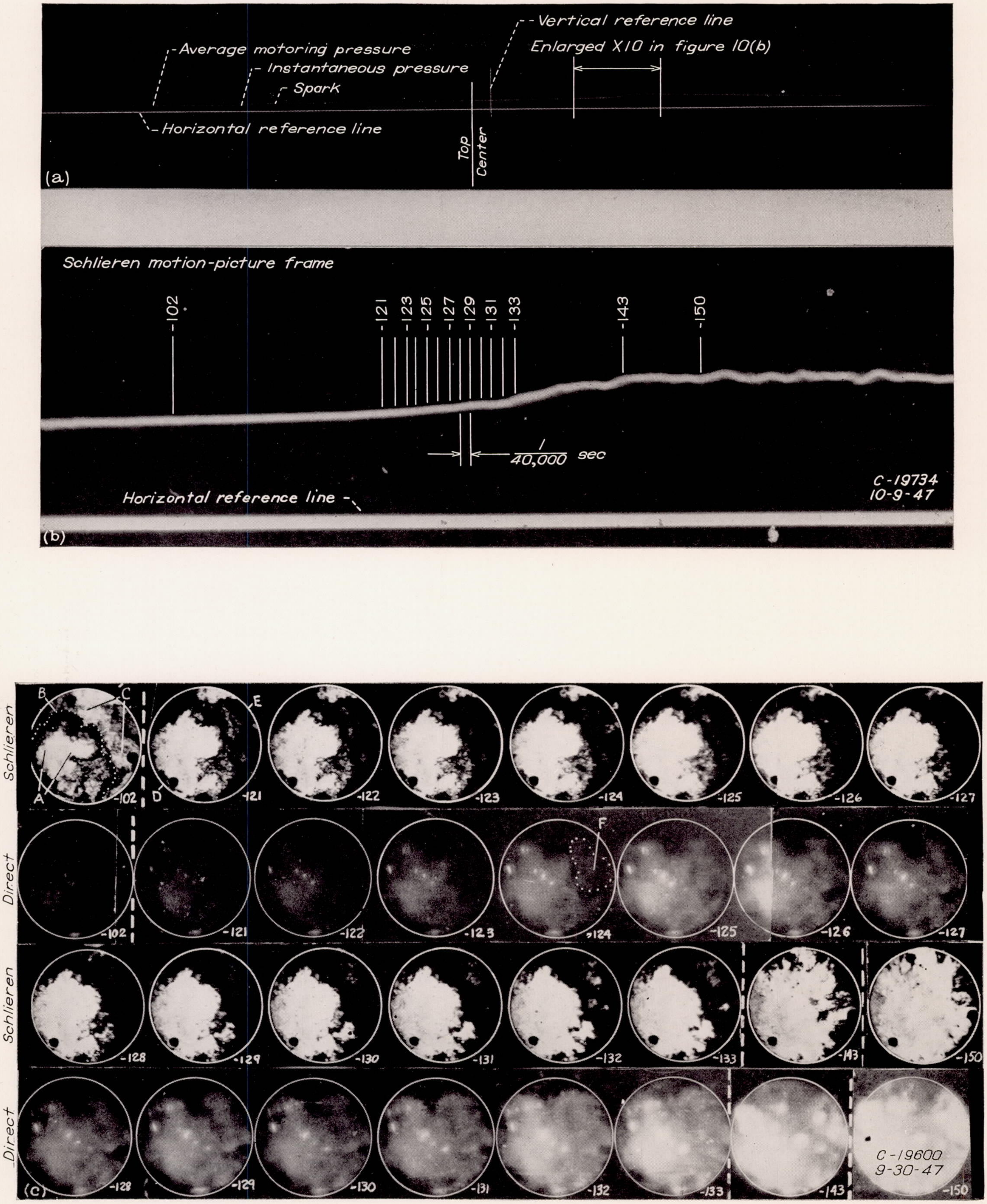


(a) Entire pressure record.

(b) Enlarged portion of pressure record; magnification, X10.

(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, white dots (insertion) outlining first end-zone luminosity.

FIGURE 9.—Knocking combustion of n-heptane fuel showing end-zone luminosity spreading forward from normal flame front.



(a) Entire pressure record.
(b) Enlarged portion of pressure record; magnification, X10.
(c) Simultaneous direct and schlieren high-speed motion pictures: A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, white dots (insertion) outlining first end-zone luminosity.

FIGURE 10.—Combustion of n-heptane fuel showing violent autoignition without knock vibrations.

In the present experiments, the simple shape of the end zone (resulting from the use of a single spark plug) made the end-zone reactions easily distinguishable in most cases. Table I, column 2, indicates the number of frames by which the first signs of the slow reaction in the schlieren pictures precede the end-zone luminescence. The reactions show as various types of gradual mottling in the end zone. For example, in figure 6, the mottling develops in an almost uniform manner over the entire end zone. In figure 11, the mottling first appears as a localized dark area immediately ahead of the flame front. All other explosions show both localized and general mottling in various proportions. All the schlieren photographs show mottling in the end zone long before luminosity in the end zone is detectable.

In three of the direct photographs, end-zone luminosity is evident before the pressure record shows the knock to have begun. The relations for all the runs are in table I, column 3. In figure 6, the luminosity is visible in frame 30 before top center; the pressure record shows no knock until between frames 27 and 26 before top center, or 3½ frames later. The diaphragm of the pressure pickup was directly in contact with the gases first showing luminosity, and no delay caused by pressure-wave-transit time across the combustion chamber could have been involved. In figure 9, the luminosity is visible in frame 44 before top center. The pressure record does not show knock until frame 42 before top center, or two frames later. In this case, the earliest luminous zone was about 2 inches from the pressure-pickup diaphragm. Had a pressure wave started from the luminous zone in frame 44 with a speed of 2000 feet per second, it would have arrived at the pickup diaphragm two frames later, or at frame 42. The end-zone luminosity thus may have first appeared at the same moment that the knock occurred. The analysis of figure 11 was the same as that of figure 9. Figure 6 may have been the only one in which end-zone luminosity appeared before the knock occurred.

The preknock reactions, as seen in the schlieren photographs, are important because they may give some indication of the chemical condition of the end gas at the moment that the violent knock reaction commences. If the chemical condition of the end gas is known, the chemical processes of the knock reaction may be more readily analyzed. Two questions have arisen concerning the preknock mottling since it was first reported in reference 7:

1. Are the disturbances represented by the mottling a form of oxidation reaction?

2. If they are oxidation reactions, are they releasing heat rapidly enough to be classified as flames?

In these experiments, no evidence was obtained that would permit any conclusive statement as to whether or not end-gas oxidation was occurring during most of the preknock mottling period. Other investigators, however, such as Withrow and Rassweiler (reference 8) have obtained spectrographic evidence of the presence of an oxidation product, namely formaldehyde, in the end gas of an engine operating under knocking conditions.

A further distinct possibility exists, however, that mottling in the end zone may represent fuel dissociation with varying degrees of oxidation. The fact that the end gas theoretically attains a temperature of 1350° F by adiabatic compression introduces the probability that at least part of what is seen as schlieren mottling represents the complicated situation of thermal and catalytic dissociation, or cracking of the fuel molecules in the presence of oxygen. The dissociation of the fuel molecules, neglecting any oxidation effects, would be accompanied by an expansion of their volume (due to the increased number of molecules) and an absorption of energy from surrounding molecules due to the endothermic nature of the cracking process. This dissociation theory possibly explains the preknock flame motions and end-zone mottlings described in previous NACA investigations (references 9 and 10), which were interpreted as exothermic combustion reactions. The possibility could be experimentally determined by adiabatically compressing a mixture of fuel and an inert gas to end-gas conditions and observing any dissociation reactions with a schlieren apparatus similar to that used in the present experiments. The effect of oxygen could be ascertained by diluting the inert gas with oxygen in various proportions. Any cracked molecules probably would react quickly with oxygen, thus furnishing a ready supply of energy to accelerate the process until some equilibrium condition was achieved or the reaction was completed.

If, in answer to the first question, the mottling is assumed to represent oxidation reactions, the second question may be asked: "Are the reactions releasing heat rapidly enough to be classified as flames?" The authors of reference 7 raised the question, concerning the degree of reaction represented by a homogeneous end-zone mottling appearing 0.006 second before the knock, whether the apparently exothermic reactions in the end zone are sufficiently intense to emit visible light. This speculation has been experimentally verified to a limited degree in figure 6 in which luminosity was apparent 3½ frames before knock. Thus it would seem that in some instances the final stages of the preknock mottling may be considered to represent inflamed gases.

In the photographs other than figure 6, all of which after analysis fail to show luminosity before knock, the explanation may be that the photographic method is insufficiently sensitive.

In reference 7, the behavior of the end zone undergoing gradual darkening before knock seemed to indicate that considerable pressure was being developed as the end-zone gases darkened. "When the motion pictures presented herein are projected, this momentary reverse movement in the combustion front is visible. As the front proceeds into the end zone, it appears to stop momentarily at the time the field in the end zone starts to show the darkening already discussed. The combustion front then proceeds again in the forward direction."

The schlieren photographs taken in the studies presented herein show no sudden vibrations or motions of any kind in the end zone as the mottling begins to develop. There is no hesitation of the flame; it goes on consuming the end zone up to the moment of knock as if nothing were happening there. This steady flame progress occurred in all runs regardless of whether n-heptane or M–4 reference fuel was used. Any pressure rise due to preknock reactions was so small that it failed to cause a noticeable increase in the rate of rise of the pressure record or to affect the normal flame movement. The preknock end-zone reactions described in previous NACA reports may have been more intense than those of the present experiments.

FIRST EVIDENCES OF KNOCK ON PRESSURE RECORDS AND HIGH-SPEED PHOTOGRAPHS AND THEIR CHRONOLOGICAL CORRELATION

The deflection in the pressure records that indicates the beginning of accelerated combustion occurs at different crank positions in different explosions. Table I, column 4, pointing out this variation, shows that the first deflection occurs as early as 4° B.T.C. and as late as −2° B.T.C. (A negative sign in front of a value indicates that the crank has passed top center.)

In figures 9 and 11 to 13, pressure-record enlargements show the initial deflections as the beginning of a momentary surge. The duration of the pulses varies from 1/10,000 second to 1/20,000 second. In other explosions, except for figure 10, the first deflection was so quick that the recording spot moved too fast to leave a continuous record on the film. Table I, column 5, listing the pressures at the moment when the first pulse occurred, shows them to vary from about 420 to 560 pounds per square inch. The height of the pressure surges, when they occurred, varied from one explosion to the next. A comparison of surging pressure records with corresponding schlieren photographs shows no correlation between size of end zone and height of pressure surge.

It should be emphasized that the momentary smooth pulses, evident on the pressure record as the first sign of knock, would have appeared as violent irregularities in previous NACA pressure records. An explanation, as set forth in the section Apparatus and Procedure, lies in the relatively small ratio of pressure-deflection modulus to time-abscissa tracing rate used in the experiments herein. The discontinuities visible on the pressure records in this report would have been even more abrupt in the previous records had the older recording system had adequate photographic speed to catch them.

Near the time of the first pressure surges, the schlieren photographs show a sudden diffuse blackening of the already darkened end zone. Table I, column 6, indicates that the sudden blackening occurred as early as five frames before the surge and as late as one frame after the surge. The schlieren photographs presented herein show the sudden blackening fairly well in frame −13 of figure 7, frame 24 of figure 8, and frame 4 of figure 11. In other explosions, the photographs have to be examined as motion pictures in order to distinguish the sudden blackening from the confused but relatively static dark pattern that exists in the end zone before the first pressure-record deflection. The rapid darkening and the motions were the only signs that indicated the onset of knock.

It was found in reference 9 that the rapid reaction, first visible as a slight blur in the high-speed schlieren photographs, was simultaneous with the beginning of violent gas vibrations. Both pressure records and motion pictures indicated subsequent violent vibrations of the gases within the combustion chamber. The experiments presented herein indicate the same sort of relation; however, certain differences exist in the appearance of the pictures. The schlieren flames in the present experiments were diffuse in appearance just before the knock; hence, any blurring of the sort described in reference 9 could not have been seen. The present experiments show instead a sudden diffuse blackening in the usually already dark end zone followed by a rapid clearing of the schlieren combustion pattern. Other work done with the same experimental engine also indicates the lack of schlieren blurring at the onset of knock. This lack of blurring and other points of difference between the results of reference 9 and the results herein may be ascribed to the use of heated inlet air, a different fuel, a different engine, and a different optical system.

End-gas temperatures less than 0.000025 second before knock were estimated by using the relation

$$\frac{T_2}{T_1}=\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

where

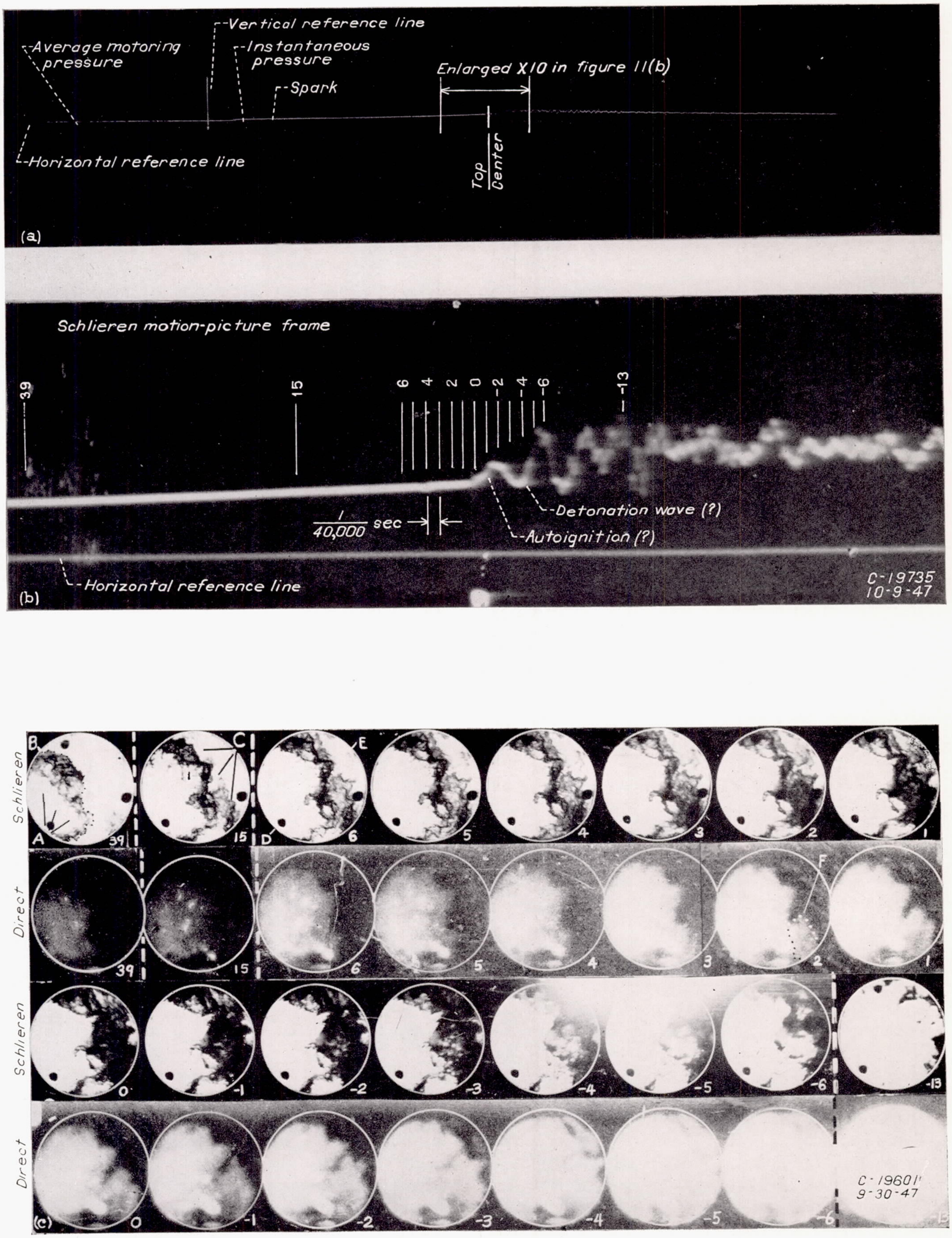
T_2 end-gas temperature immediately before knock, °R
T_1 precompression charge temperature, °R
p_2 combustion-chamber pressure immediately before knock, pounds per square inch absolute
p_1 precompression charge pressure, pounds per square inch absolute
n polytropic-compression exponent

It was necessary to assume that negligible heat was being released by preknock end-zone reactions. A value of 1.3 was chosen for n. The end-gas temperatures thus computed are listed in degrees Fahrenheit in table I, column 7. They range from 1310° to 1430° F. For the seven n-heptane runs, the values of end-gas temperatures range between 1310° and 1390° F. The pressure ratios p_2/p_1 from which the temperatures were computed are shown in table I, column 8. The relatively narrow range of values for the end-gas temperatures is a reflection of the decreasing sensitivity of the function $\left(\frac{p_2}{p_1}\right)^{\frac{1.3-1}{1.3}}$ to increasing values of p_2/p_1. If the time-pressure conditions to which the end gas was subjected had been altered by changing engine-operation settings such as spark timing or compression ratio, the knock probably would have occurred at a different time or pressure or both. This effect has been demonstrated in a continuously running engine (reference 11).

KNOCK REACTION

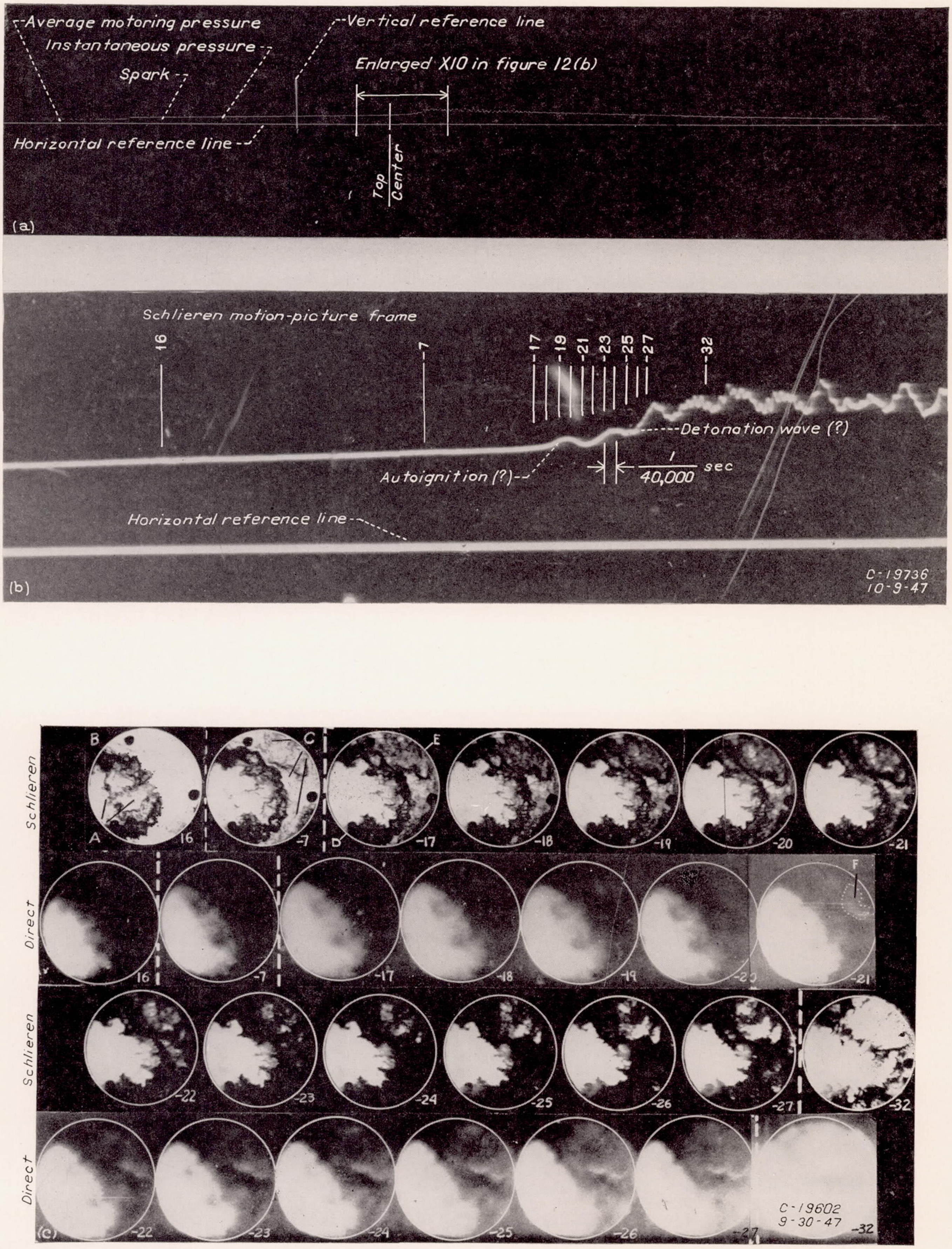
When the schlieren photographs are projected as motion pictures, the sudden blackening and the violent expansion surge that initiate the characteristic periodic vibrations of the combustion-chamber gases seem unmistakably and intimately associated in time and space. This relation is impossible to see in the still pictures presented herein (except for fig. 7) because of the confusion resulting from the inability to distinguish between the static and the rapidly moving portions of the schlieren pattern in the end zone.

The pressure records of figures 9 and 11 to 13 indicate that the rapid reaction that marks the initiation of gas vibrations may progress to completion in two stages. The first stage appears as a smooth rise and fall, or pulsation; the second stage is marked by a discontinuity. Perhaps this discontin-



(a) Entire pressure record.
(b) Enlarged portion of pressure record; magnification, X10.
(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, black dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, black and white dots (insertion) outlining first end-zone luminosity.

FIGURE 11.—Knocking combustion of n-heptane fuel showing autoignition possibly followed by a violent detonation wave.

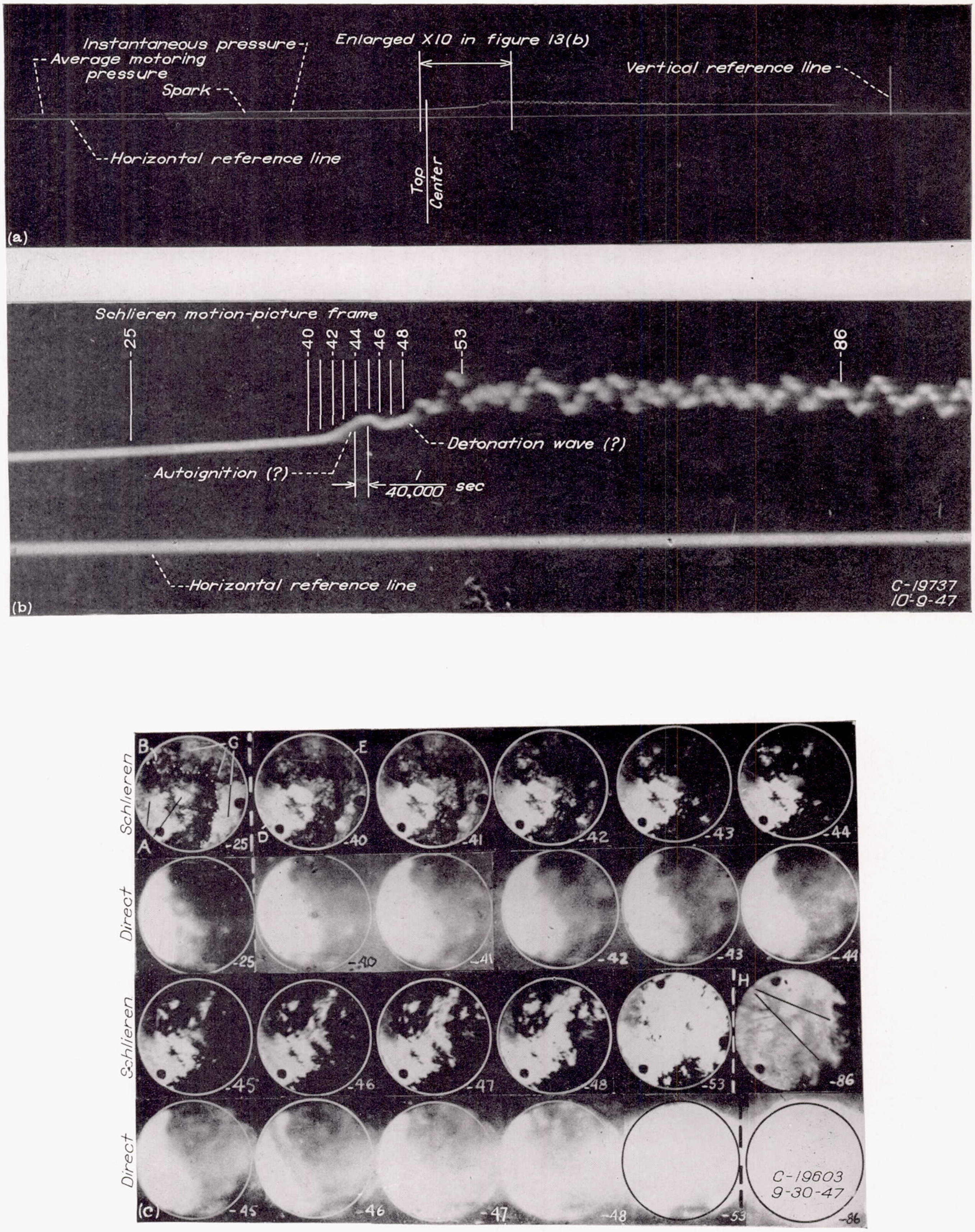


(a) Entire pressure record.

(b) Enlarged portion of pressure record; magnification, X10.

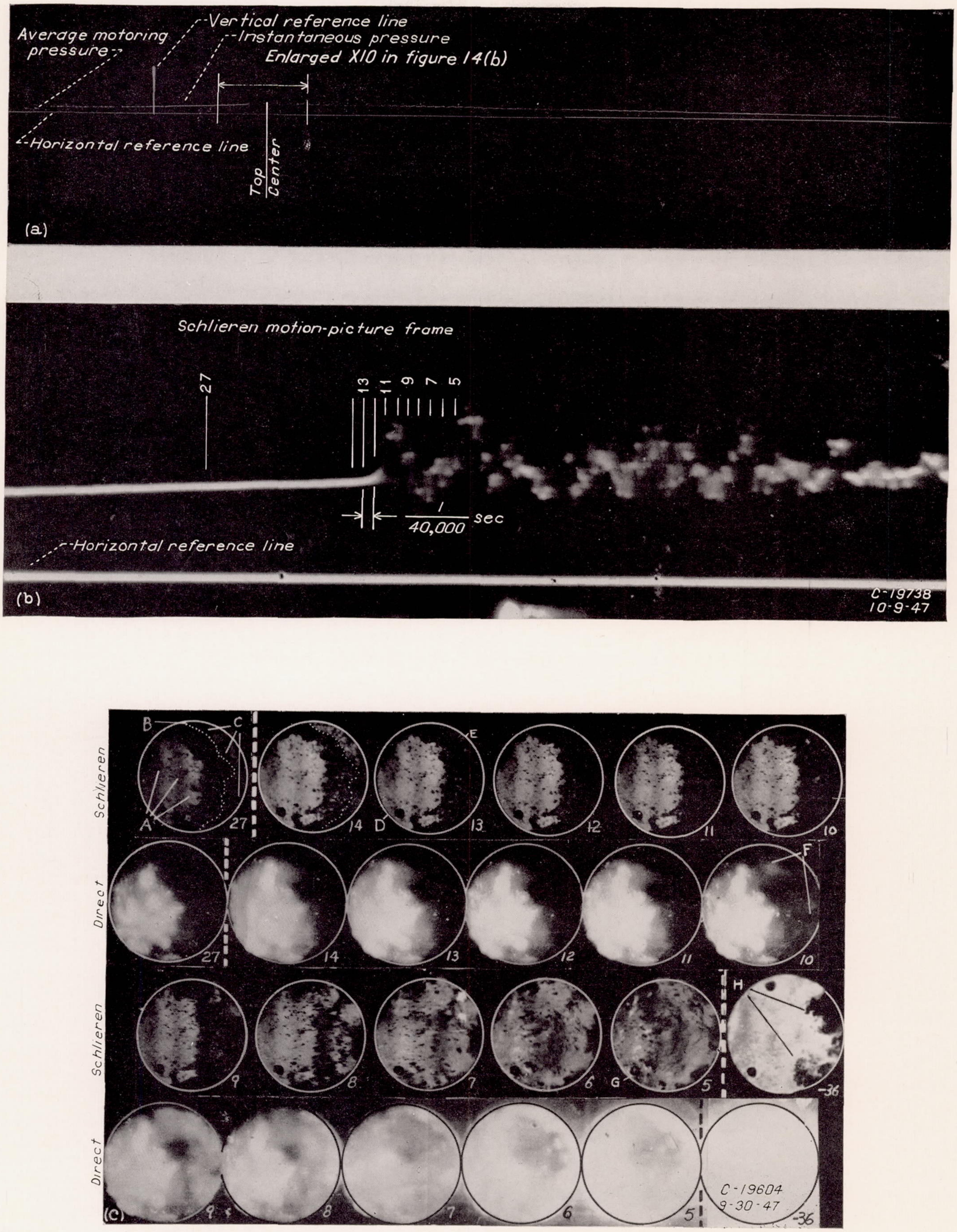
(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, black dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, white dots (insertion) outlining first end-zone luminosity.

FIGURE 12.—Knocking combustion of n-heptane fuel showing autoignition possibly followed by a very mild detonation wave.



(a) Entire pressure record.
(b) Enlarged portion of pressure record; magnification, X10.
(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; H, smoke.

FIGURE 13.—Knocking combustion of n-heptane fuel.



(a) Entire pressure record.

(b) Enlarged portion of pressure record; magnification, X10.

(c) Simultaneous schlieren and direct high-speed motion pictures; A, zone of completed combustion; B, white dots (insertion) emphasizing normal flame front; C, end zone showing mottling in schlieren photographs caused by slow preknock reactions; D, spark-plug location; E, pressure-pickup location; F, initial end-zone luminosity; G, gases within screwhead socket rendered luminous by pressure wave; H, smoke.

FIGURE 14.—Violently knocking combustion of M-4 fuel.

uity is a manifestation of a detonation wave as reported in reference 1. The initation of gas vibrations in two stages suggests that knock may sometimes be preceded by autoignition, sufficiently violent in itself to cause gas vibrations, followed by a detonation wave, which makes the reaction even more violent. It seems that the autoignition process alone may or may not be sufficiently rapid to cause gas vibrations. Figure 10 is clear proof of this presumption. Here, a very large end zone underwent autoignition without a trace of periodic gas vibrations in the motion pictures or on the pressure record. Figure 12 shows a mild knock possibly developing as violent autoignition in frame −18 on the pressure record followed by some kind of discontinuity between frames −25 and −26 so abrupt that vibrations of 80,000 cycles per second were excited (probably within the pickup). This discontinuity may be an indication of the passage of a detonation wave. When the photographs are viewed as motion pictures, the vibrations seem to start in frame −18 and no evidence of a detonation wave can be seen in frame −25 or −26. The wave could not have been violent, as can be seen from the pressure record. This mildness may be why it was missed in the motion pictures.

The sudden blackening resembles the propagated homogeneous autoignition observed in another investigation. A comparison among frames −13 to −16 in figure 7 and similar pictures from the other investigation clearly shows this relation. This abnormal form of combustion may be a borderline case between homogeneous autoignition and a detonation wave. Other explosions of the present series show an easily visible fast spatial propagation of autoignition when viewed in motion pictures, but the still pictures fail to show this form of autoignition.

The means by which the considerable volume of the end gas could become intensely reactive throughout a sufficient proportion of its bulk in a short enough time to cause gross pressure discontinuities has been a point of speculation and investigation for decades. Ricardo (reference 12) proposed what has become known as the simple autoignition theory of knock. As he expressed it: "Now when the residual unburnt portion of the charge is compressed and heated by the burning portion to a point above its self-ignition temperature it will ignite instantaneously throughout its whole bulk, and the local rise in pressure due to this instantaneous ignition is so sudden as to cause the cylinder walls to spring in much the same manner as though they had been struck by a hammer." Other investigators believed that some sort of detonation wave passed through the end gas, completing the combustion in a sufficiently short period to cause gross pressure discontinuities (reference 1).

The principal objection to the simple autoignition theory is that it assumes perfect homogeneity of composition and condition in the end gas. The relation between the degree of homogeneity and the velocity of sound in the end gas necessary for the formation of either shock-forming homogeneous autoignition or a rapidly moving wavelike mechanism, such as a detonation wave, is discussed in reference 1. It is concluded there that either is possible, depending on the conditions. The present experiments support this concept of the two possibilities.

The motion pictures show that in four cases, namely figures 6 to 8 and 14, the surge reaching the wall opposite the end zone for the first time momentarily raises the temperature thereabouts so high that the direct radiation from the gases located just above the screw head is recorded by the schlieren camera. As previously stated, the schlieren photographs are taken by the reflection of externally supplied light by the mirror composing the piston top, because ordinary flame reactions are insufficiently actinic to record. A nonreflecting portion of the piston top is normally a black spot. Striking evidence of the speed with which the knock reaction may proceed to completion is that the schlieren patterns in the four aforementioned explosions have almost entirely cleared before the pressure wave from the reaction causes the extraordinary illumination at the wall described. This illumination is visible in the still photographs of these four explosions presented.

SUMMARY OF RESULTS

Simultaneous direct and schlieren photographs at 40,000 frames per second and correlated pressure records were taken of knocking combustion in a spark-ignition engine.

End-zone luminosity was preceded in all cases by extensive darkening of the end zone as viewed by the schlieren system. In one explosion, the direct photographs indicated end-zone luminosity preceding the beginning of fluctuations on the pressure record by more than three frames. This explosion thus indicated that the final stages of the preknock end-zone reaction shown in the schlieren photographs were intense enough to photograph and be classified as flame and so substantiated, to a limited extent, the conclusions of previous NACA reports that the preknock end-zone mottling in the schlieren system represented autoignition flames. Schlieren frames showing early stages of autoignition were unaccompanied by corresponding inflections in the pressure record and luminosity of the end zone. Early stages of autoignition were thus probably low-energy reactions even though quite extensive within the end zone.

The blur of the schlieren photographs precisely denoting the beginning of knock in earlier NACA experiments was imperceptible in the present schlieren photographs. In at least one instance, the final stages of autoignition seemed to merge into a propagated homogeneous autoignition resembling that previously reported by NACA investigators. A violent expansion of the end zone accompanied the propagated homogeneous autoignition when the schlieren photographs were viewed as motion pictures. From the appearance of the schlieren photographs at the time of knock, it was impossible to say whether or not a detonation wave similar to those described in previous NACA reports had passed through the end zone. Some pressure records, however, show combustion-pressure pulsations of varying height followed by a discontinuity (probably a detonation wave).

Extensive autoignition without knocking vibration occurred once, showing that autoignition alone may sometimes be incapable of exciting gas vibrations.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *September 16, 1947*.

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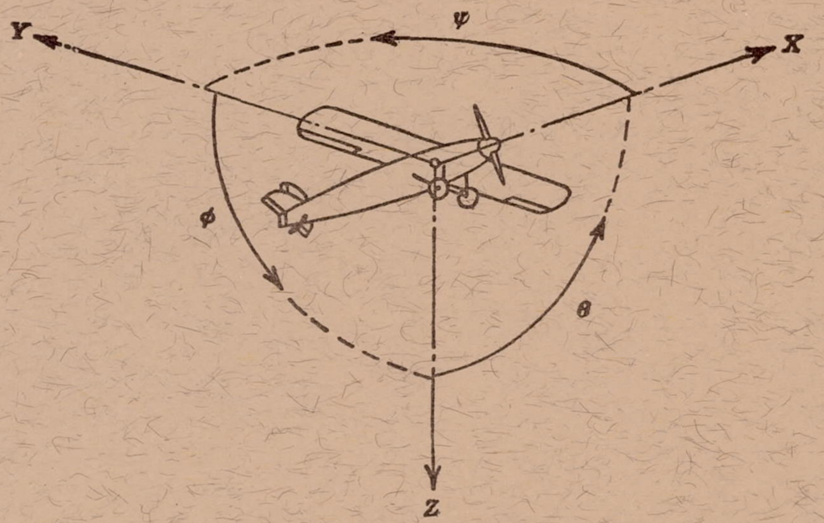

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D	Diameter
p	Geometric pitch
p/D	Pitch ratio
V'	Inflow velocity
V_s	Slipstream velocity
T	Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q	Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$
P	Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s	Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
η	Efficiency
n	Revolutions per second, rps
Φ	Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph
1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft